Annales Geophysicae, 23, 2511–2517, 2005
SRef-ID: 1432-0576/ag/2005-23-2511

Annales Geophysicae

Manifestation of solar activity in the global topside ion composition – a study based on satellite data

V. Truhlík, L. Třísková, and J. Šmilauer

Institute of Atmospheric Physics, Acad. Sci. Czech Rep., Boční II., 14131 Praha 4−Sporilov, Czech Republic

Received: 6 February 2005 – Revised: 8 July 2005 – Accepted: 22 July 2005 – Published: 14 October 2005

Abstract. The solar cycle variation of the most important parameters characterizing the ion composition in the topside ionosphere is studied. For this purpose data from the ACTIVE mission (the IK-24 satellite) for the maximum of solar cycle 22 (aver F10.7∼200), complemented by data available from the Atmosphere Explorer (AE) satellites, for the minimum of solar cycle 21 (average F10.7∼85), were processed. OGO-6 data from the low maximum of solar cycle 20 (average F10.7∼150) were used for medium solar activity conditions. The results for the equinox from the recently developed empirical model of ion composition are analyzed and presented, and typical vertical profiles from solar maxima and minima are shown. It was found that the logarithm of the O^+, H^+, He^+, and N^+ densities in the topside ionosphere at a fixed altitude, latitude, and local time is, in the first approximation, a linear function of solar activity characterized by the daily F10.7. On the other hand, the upper transition height is generally a non linear function of the daily F10.7, the deviation from linear dependence increases with latitude.

Keywords. Ionosphere (Plasma temperature and density; Ion chemistry and composition; Modeling and forecasting)

1 Introduction

Different ion species in the topside ionosphere are produced by photo ionization and chemical reactions in this region or result from transport processes. The most important ions are O^+, H^+, He^+, and N^+. Their fractions strongly depend on various geophysical parameters, such as latitude, altitude, local time, season and solar and geomagnetic activity. Some minor ions as O^{++} and N^{++} in the upper part and NO^+, O_2^+ and N_2^+ in the lower part of the topside ionosphere are also present. An example of the ion composition of the outer ionosphere as measured on board the satellite during the ACTIVE mission is shown in Fig. 1.

Correspondence to: V. Truhlík
(vtr@ufa.cas.cz)

Many experimental and theoretical studies during the last three decades have revealed the most important features of the ion composition in the topside ionosphere. Johnson (1966) showed a vertical profile of ion composition up to the altitude of 1200 km for day and solar minimum based on rocket and satellite data. Taylor et al. (1970) studied latitudinal variations in the distribution of the primary ions obtained from OGO-2 and OGO-4 satellites in the upper ionosphere during the period of rising solar activity (1965–1968). They have found the existence of the high-latitude light ion trough, a deep trough in He^+ near the dipole equator, and the He^+ winter bulge. Using ion mass spectrometer data from the OGO-6 satellite, the distribution of prominent and trace ions and the occurrence of the light ion troughs was pointed out by Taylor (1973). The geomagnetic vs. local time distribution characteristics of the ionic constituents (O^+, H^+, and He^+) from the ISS-b satellite was investigated in Matuura et al. (1981). Köhlein (1989) proposed an empirical model of atomic ion densities up to 4000 km altitude for quiet geophysical conditions during low and medium solar activity. Hoegy et al. (1991) compared their database (based on satellite measurements made during 70's and 80's) with results from several empirical and theoretical models for lower mid-latitudes, daytime and low and medium solar activity. They have noted that H^+ and He^+ decrease with increasing solar activity, whereas N^+, O^+ increase. Heelis et al. (1990), for the first time, reported a possible dominance of He^+ at mid-latitudes for solar maximum. Gonzalez et al. (1992) have dealt with seasonal variation of concentrations of light ions in the equatorial ionosphere during solar minimum. They have found a discrepancy in densities from the ion mass spectrometer and the retarding potential analyzer on board the Atmosphere Explorer E satellite. Craven et al. (1995) have compared a theoretically modeled (the FLIP model) and measured ion densities (the Atmosphere Explorer data) in the mid-latitude ionosphere up to 1400 km for low solar activity conditions. West et al. (1997) have dealt with the solar activity variations in the composition of the low-latitude topside ionosphere based on DMSP F10 data. The effects of neutral winds and of the EUV solar flux in the behavior of the upper

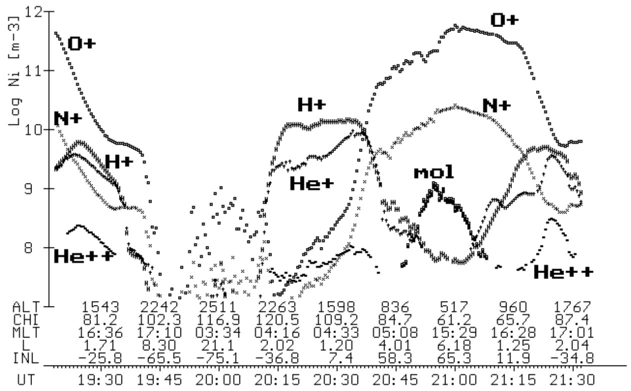

Fig. 1. Example of ion composition between 500 and 2500 km as measured by the ion mass spectrometer on board the IK-24 satellite (ACTIVE mission) including minor ions. ALT-altitude, CHI-solar zenith angle, MLT-magnetic local time, L-McIlwain parameter, INL-invariant latitude, UT-Universal Time, mol-molecular ions (N_2, NO^+), 15 April 1990.

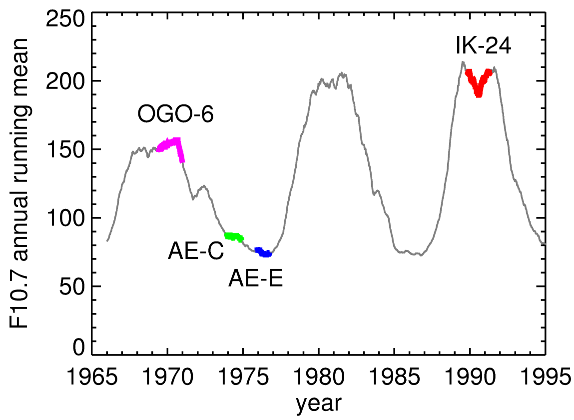

Fig. 2. Periods of data used from OGO-6, AE-C, AE-E, and IK-24 satellites with corresponding solar activity.

transition level at low mid-latitudes under low and moderate solar activity is the subject of the paper by MacPherson et al. (1998), based on the Incoherent Scatter data from Arecibo and the SUPIM model. A statistical analysis of the dependence of the topside ion density on the solar flux from ISS-b at 1100 km during solar maximum is given by Iwamoto et al. (2000). They have confirmed that the H^+ density has a negative correlation with the solar flux F10.7 while O^+ has a positive correlation. Gonzalez et al. (2004) have analyzed the general solar cycle variability of the nighttime He^+ layer near the autumnal equinox over Arecibo.

In spite of this, variation of the ion composition with solar activity is not fully understood, especially as regards to its quantitative description and global distribution for the solar maximum. Long series of data records, covering various solar activity levels at different latitude, altitude and local time ranges, needed to describe the ion composition response to the EUV flux, are rare so far.

A new global empirical model of the relative ion composition in the outer ionosphere is used in this study, further on referred to as the TTS (Truhlík, Třísková, Šmilauer) model. It was introduced in Třísková et al. (2003) and validated in Truhlík et al. (2003); Truhlík et al. (2004). To obtain absolute ion densities the TTS model has been complemented by a recently developed model of the electron density, also for the region of the topside ionosphere (Třísková et al., 2005)[1] Special attention is paid to the manifestation of solar activity in the densities of ion species at a fixed point. Vertical profiles of ion densities and the upper transition level are also presented.

2 Data description

Our database of thermal plasma parameters contains the results of many available satellite ion mass spectrometer (IMS) measurements covering the period from the end of the 1960's to the beginning of the nineties. But for this study only data from three typical solar activity periods were chosen (Fig. 2, and Table 1).

In recent years, it has been demonstrated by using different instruments on board a number of satellites (e.g. Atmosphere Explorer and OGO series) that the relative ion composition for low and medium solar activity was measured essentially correctly (e.g. Grebowsky et al., 1970; Hoffman et al., 1969), in spite of some differences in absolute ion densities, which occurred especially on AE-E (e.g. Gonzalez et al., 1992). For high solar activity, however, only ion densities in the altitude range from ~500 km up to ~3000 km measured on board the IK-24 satellite by a Bennett ion mass spectrometer (BIMS) were available. Unfortunately, a huge data-base from RPA measurements on board the DMSP satellites covers fixed altitude and fixed local time only, and RPA measurements do not provide information as detailed as ion mass spectrometers (e.g. this technique is not capable of detecting N^+ and distinguishing reliably between H^+ and He^+ in the topside).

The IK-24 ion mass spectrometer data, on the other hand, could only be validated recently by comparing it with newly processed results of measurements made on board the same spacecraft, using the Retarding Potential Analyser (RPA) method (Truhlík et al., 2004). A good agreement of the IMS with the RPA probe data was found, which speaks in favour of both measurements being correct, because the procedures for determining the ion densities are independent: correction of the discrimination of ions by atomic weight for the spectrometer, and calculation of the ion densities from the volt-ampere characteristics for the RPA method.

[1] Třísková, L., Truhlík, V., and Šmilauer J.: An empirical topside electron density model for calculation of absolute ion densities in IRI, Adv. Space Res., accepted, 2005.

Table 1. Characteristics of the data used.

Satellite	Average F10.7	Time period	Altitude (km)	Latitude (deg)	LT (h)
OGO-6	150	June 1969–December 1971	400–1100	±83	0–24
AE-C	85	December 1973–November 1974	130–4300	±68	0–24
AE-E	75	December 1975–October 1976	130–2400	±20	0–24
IK-24	200	October 1989–November 1991	500–2500	±83	0–24

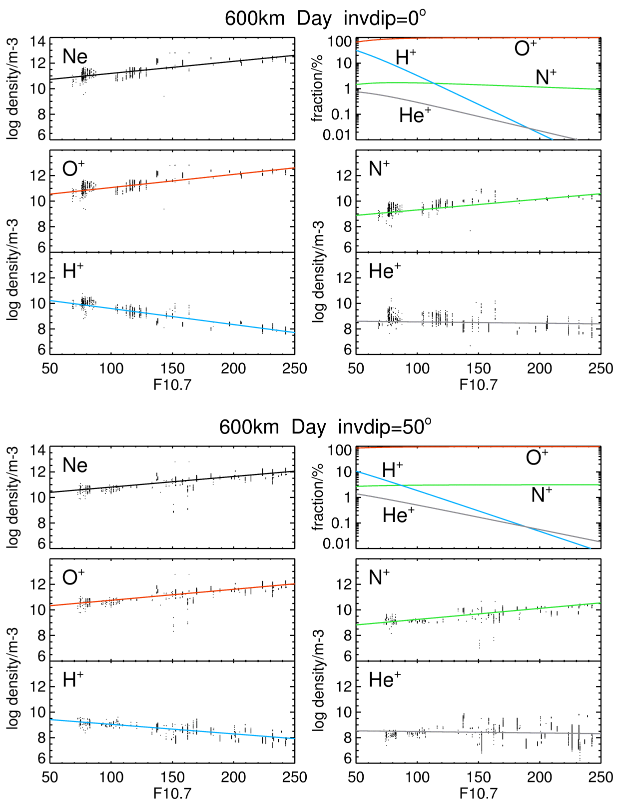

Fig. 3. Dependence of the logarithm of the individual ion densities, of the electron (=total ion) density, and of the relative ion densities on the solar activity level characterized by the actual day values of the F10.7 index. Example for equinox, equator±15°, midlatitudes 50°±15°, altitude of 600±80 km, and daytime 13±3 h MLT. Points-measured values, lines-values calculated from the models (TTS relative ion density and electron density models).

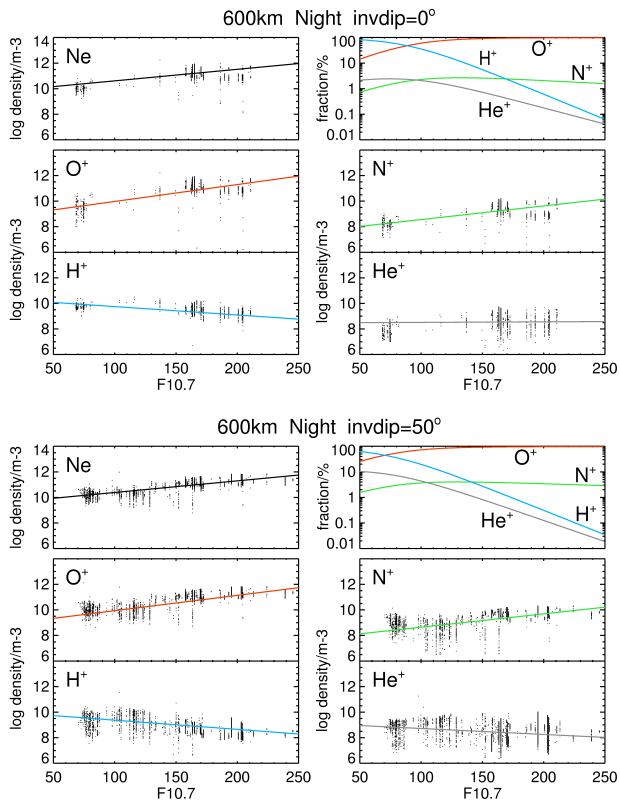

Fig. 4. Dependence of the logarithm of the individual ion densities, of the electron (=total ion) density, and of the relative ion densities on the solar activity level characterized by the actual day values of the F10.7 index. Example for equinox, equator±15°, midlatitudes 50°±15°, altitude of 600±80 km, and nighttime 0±3 h MLT. Points-measured values, lines-values calculated from the models (TTS relative ion density and electron density models).

3 Ion density dependence on solar activity

In Figs. 3 through 6, densities of the main ions vs. solar activity are plotted, and raw data from all satellites listed in Table 1 without any modification are presented. The values calculated from the TTS model are plotted, together with the data evaluated from the satellite mass spectrometer measurements. It is evident that, in the first approximation, the dependence of the logarithm of ion densities on the solar activity index F10.7 is linear.

Examples for equinoxial day and night, and altitudes of 600 and 850 km, together with interpolated densities calculated from the TTS model, are shown. The TTS model is a relative one. Absolute density values are obtained by combining this model with the recently created model of the topside electron density in the altitude range of 400 to 2500 km, which can be considered with sufficient accuracy to be equal to the total density of ions (Třísková et al., 2005). Magnetic local time (MLT) and latitude were chosen as the main coordinates. The longitudinal variation can be reduced to a

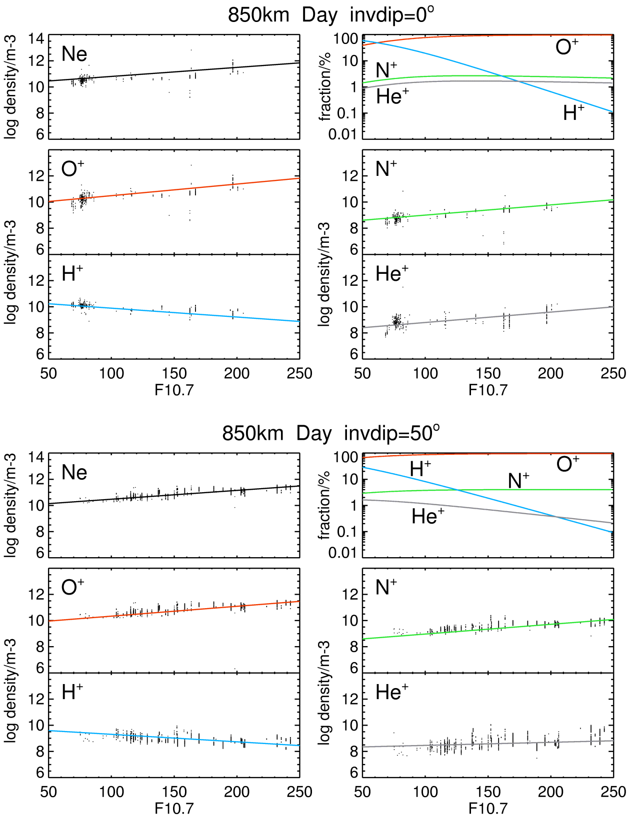

Fig. 5. Dependence of the logarithm of the individual ion densities, of the electron (=total ion) density, and of the relative ion densities on the solar activity level characterized by the actual day values of the F10.7 index. Example for equinox, equator±15°, mid-latitudes 50°±15°, altitude of 850±90 km, and daytime 13±3 h MLT. Points-measured values, lines-values calculated from the models (TTS relative ion density and electron density models).

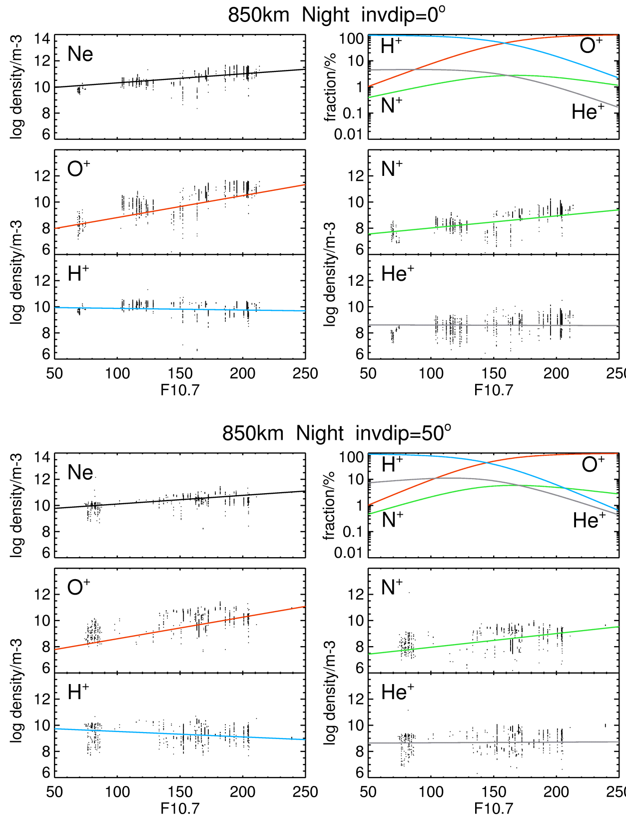

Fig. 6. Dependence of the logarithm of the individual ion densities, of the electron (=total ion) density, and of the relative ion densities on the solar activity level characterized by the actual day values of the F10.7 index. Example for equinox, equator±15°, mid-latitudes 50°±15°, altitude of 850±90 km, and nighttime 0±3 h MLT. Points-measured values, lines-values calculated from the models (TTS relative ion density and electron density models).

second-order effect, if the latitudinal coordinate takes into account the real configuration of the geomagnetic field. Therefore, a new coordinate (invdip) was introduced by Truhlík et al. (2001). Invdip is close to the dip latitude (diplat) near the equator and becomes closer to the invariant latitude (invl) at higher latitudes. The agreement of the calculated and measured dependence is satisfactory and can be considered as another validation of the TTS model.

In the left upper part of the figures the measured and modeled electron (total ion) density are shown, and the relative ion density dependence on the F10.7 index is presented in the right upper panel. The relative densities of the individual components have a considerably nonlinear dependence on solar activity, especially near the upper transition height (see also Fig. 9). From plots of relative ion densities trends in all ion species can be easily seen. The density of the O^+ ions at both altitudes studied increases with solar activity both during the day and at night, with the greatest increase occurring for 50° invdip at 850 km at night. The N^+ ions follow the changes of the O^+ density. The H^+ density decreases with increasing F10.7, with the greatest change occurring at an altitude of 600 km above the equator in the daytime and almost no change at the altitude of 850 km above the equator at night. The He^+ density showed no change in most cases, only at 600 km at night did a little decrease occur, but at the altitude of 850 km over the equator the He^+ density shows a sharp increase with solar activity during daytime hours. It is also apparent that during the daytime and during the high solar activity, the He^+ density is larger than H^+. It can even result in the dominance of He^+ ions. Such cases have been described before (Heelis et al., 1990; Shultchishin et al., 1996; Gonzalez et al., 2004) for low mid-latitudes and in (Heelis et al. (1981) and Erschova et al. (1998) for high latitudes. In the following paragraph we will address the solar activity dependence of the vertical profiles of the relative and absolute ion composition.

4 Vertical profiles

Figures 7 and 8 present examples of vertical profiles of relative and absolute ion densities, respectively, as calculated

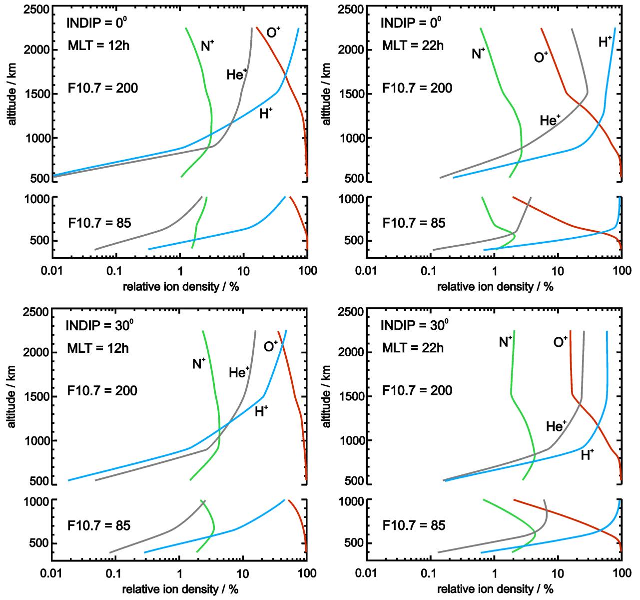

Fig. 7. Examples of equinoxial vertical profiles of the relative ion densities calculated from the TTS model for high (F10.7=200) and low solar activity (F10.7=85) and for two local times (12 h and 22 h) and two latitudes (0° and 30°).

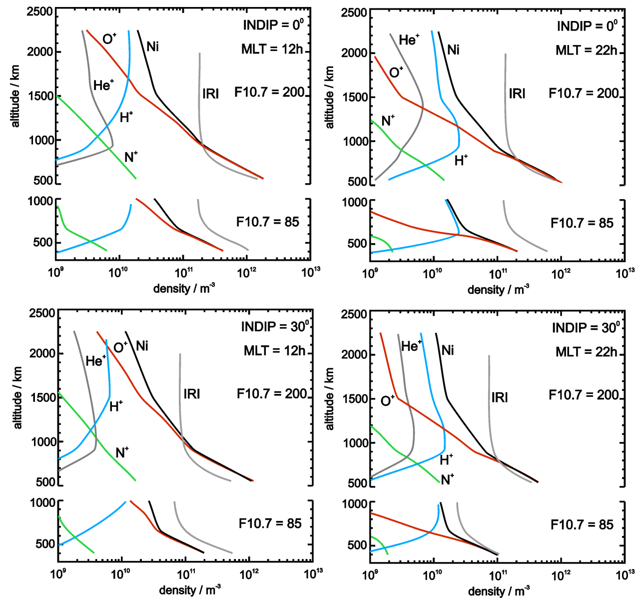

Fig. 8. Equinoxial daytime and nighttime vertical profiles of absolute densities for the four main ions as derived from the proposed N_e model and from the relative ion composition TTS model. The total ion density N_i following from our model and the IRI (Bilitza, 1990) values are shown.

from the TTS model. This model consists of submodels for three altitude levels for low solar activity and for four altitude levels for high solar activity and uses an interpolation scheme for intermediate altitudes, days of the year, and solar activities. Different model altitude levels for the solar maximum and minimum were chosen with respect to different thermal plasma distributions (characterized by the scale height, upper transition height, etc.) depending on solar activity. The electron density from the IRI 2001 model is also shown for comparison. As shown elsewhere (e.g. Bilitza, 2004; Třísková et al., 2002), the IRI model overestimates the electron density substantially in the upper topside.

To calculate the relative ion density for a given day of the year and a given solar activity level, linear interpolation between the submodels is used. The Booker (1977) formalism is employed to establish the vertical profiles. This approach assumes that the altitudinal profile of the electron/ion density can be divided into several subsections such that in every subsection, the altitude gradient is nearly constant, which is called the skeleton profile. The derivative of the skeleton function can be represented by a sum of the Epstein functions (Bilitza, 1990). Through integration, we obtain the resulting density in terms of the "Booker function". The vertical profiles of the densities based on Booker's formalism are satisfactory in the first approximation. Sometimes, however, they may display non-physical behavior, for example, discontinuity in the first derivative (visible smoothed edges) at the altitudes of the individual sub-models. Therefore, one should look for other functions.

Examples of profiles for the equinoxes, daytime and nighttime at the equator and at lower middle latitudes, at the time

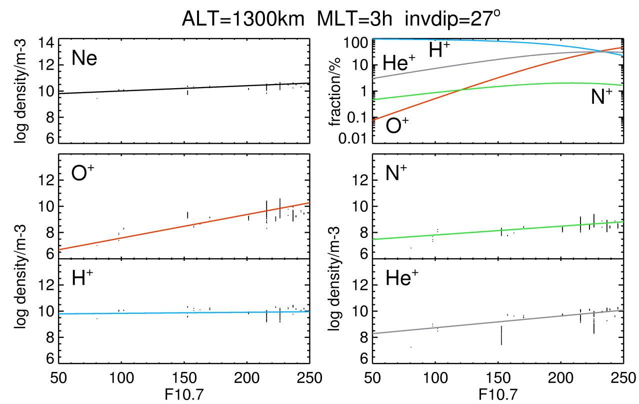

Fig. 9. Dependence of the logarithm of the individual ion densities, of the electron (=total ion) density, and of the relative ion densities on the solar activity level characterized by the actual day values of the F10.7 indes. Example for equinox, mid-latitudes 27°±15°, altitude of 1300±90 km, and nighttime 3±1 h MLT. Points-measured values, lines-values calculated from the models (TTS relative ion density and electron density models).

of high and low solar activity, are shown. During low solar activity He^+ remains a minor ion with values significantly below H^+. During high solar activity He^+ becomes a major ion and can become the dominating ion (Heelis al., 1990; Shultchishin et al., 1996; Gonzalez et al., 2004). At middle latitudes, below 1000 km, there are systematically more helium than hydrogen ions in the daytime during the solar maximum. This fact has not yet been taken into account in

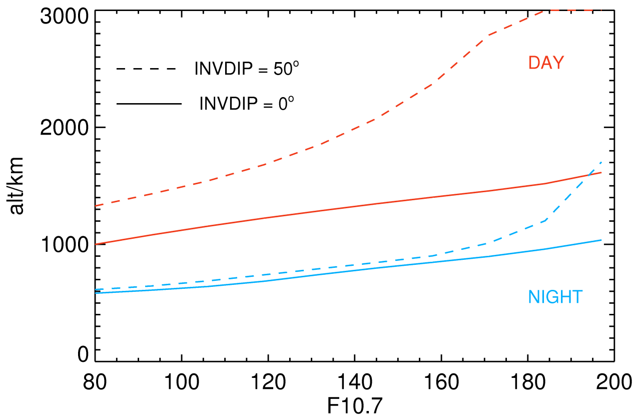

Fig. 10. Solar activity dependence of the upper transition height where n(O^+)+n(N^+)=n(H^+)+n(He^+) for equator and mid-latitudes as follows from the TTS model.

existing empirical models (e.g. the IRI model assumes a constant ratio: H^+/He^+=9). Whereas the relative densities of O^+, H^+ and He^+ display variations of several orders of magnitude in the altitude range in question, the relative density of N^+ varies within a few percent, regardless of the time of day, or of the level of solar activity.

4.1 Upper transition height

The upper transition height H_T is defined in this study as the level where the sum of densities of O^+ and N^+ equals the sum of densities of light ions (H^+ and He^+). Of course, the contribution of N^+ is very small. For high solar activity the upper transition level at a given point, at a given local time, lies much higher than for low solar activity (e.g. MacPherson et al., 1998; Třískova et al., 1998; Třísková et al., 2003). An example of the dependence of H_T on solar activity is shown in Fig. 10, where the variation of H_T at the equator and at the latitude of 50° invdip for F10.7=80 through 200 is shown for daytime and nighttime.

In Figs. 3 through 6 (lower panels) the transition of O^+ to H^+ prevalence is clearly seen for night hours, during the day the upper transition height is situated higher than 600 or 850 km. At the equator the transition occurs for higher F10.7 than at middle latitudes.

The importance of the He^+ ions increases with solar activity and the He^+ density can be equal to or even higher than that of O^+ and/or H^+. An example of such a situation (following from the TTS model and supported by the experimental data) is given in Fig. 9. At the altitude of 1300 km during the night (MLT=3h) and at low mid-latitudes the densities of O^+, H^+ and He^+ are equal for F10.7=230. At this particular local time and latitude the relative N^+ behaves similarly to He^+ rather than O^+. This could be caused by the importance of the chemical reaction of the relatively abundant He^+ with N_2 producing N^+ (Adams and Smith, 1976) at low altitudes and transporting it upwards.

5 Discussion and summary

Our database comprising the ion composition and electron density at altitudes from 400 to 3000 km made it possible to study the manifestation of solar activity in the densities of the individual ion species for different latitudes and local times. The paper deals with the equinox period - the behavior of the major ion densities in the topside ionosphere at solstices will be the subject of further studies.

For the first time, the behavior of the densities of the four most important ions in the outer ionosphere has been shown over such a large range of solar activity. The density of ions with medium atomic weight always increases with increasing solar activity. The reason is an increase in the F2 layer density (almost O^+ only) and also the increase in the ion temperature and corresponding scale height. Unlike the O^+ density, the density of H^+ decreases with increasing solar activity, or it remains almost constant. To explain this we remind the reader of the well-known fact that H^+ in the topside ionosphere is formed by the following charge-exchange reaction:

$$H^+ + O \leftrightarrows O^+ + H$$

(e.g. Lemaire and Gringauz, 1998). During the night we can neglect the transport of ions and the time derivative of n(H^+) in the topside ionosphere and for the H^+ density it approximately holds:

$$n(H^+) = \frac{9}{8}\frac{n(H)}{n(O)}n(O^+).$$

Using the MSIS 86 model (Hedin et al., 1987) we find that the ratio n(H)/n(O) decreases by about 2-3 orders of magnitude from solar minimum to solar maximum. From Figs. 3 through 6 it follows that n(O^+) rises by about 1–2 orders of magnitude only. The combined effect is a decrease in H^+ by as much as 2 orders of magnitude.

The logarithm of the absolute density of the main ions (O^+, H^+, He^+, N^+) at a given altitude, latitude, local time, and season (equinoxes in our case) is, in the first approximation, a linear function of the solar activity characterized by the F10.7 index (see the lower panels of Figs. 3 through 6 and Fig. 9).

The presented results also confirm the importance of the increasing He^+ density with increasing solar activity. Under high solar activity at altitudes below 1000 km, the He^+ density is regularly up to one order higher than that of H^+ during the day (Figs. 7 and 8). Above 1000 km sometimes the amounts of O^+, H^+, and He^+ may be equal. This fact has not yet been reflected in the existing empirical models (IRI and Köhnlein, 1989).

For representation of vertical profiles of the individual ion densities other functions than that corresponding to the Booker's formalism should be determined. The best would be such that would physically describe the vertical distribution of ion densities.

Acknowledgements. We are grateful to NSSDC and to the experiment PIs J. H. Hoffmann, H. C. Brinton, and H. Taylor Jr. for providing the AE-C, AE-E, and OGO-6 data. This research was partly supported by Grant No. 205/02/P037 of the Grant Agency of the Czech Republic, by Grant No. 205/03/0953 of the Grant Agency of the Czech Republic and by Joint Grant ME651 of the Grant Agency of the Ministry of Education of the Czech Republic and the US National Science Foundation No.0245457.

Topical Editor M. Pinnock thanks D. Bilitza and M. K. Goel for their help in evaluating this paper.

References

Adams, N. G. and Smith, D.: Production distributions for some ion-molecule reactions, J. Phys., B9, 1439–1452, 1976.

Bilitza D.: International Reference Ionosphere 1990, National Space Science Data Center, NSSDC 90-22, 71-76, Greenbelt, MD, 1990.

Bilitza, D.: A correction for the IRI topside electron density model based on Alouette/ISIS topside sounder data, Adv. Space Res., 33(6), 838–843, 2004.

Booker, H. G.: Fitting of multiregion ionospheric profiles of electron density by a single analytic function of height, J. Atmos. Terr. Phys., 39, 619–623, 1977.

Craven, P. D., Comfort, R. H. , Richards, P. G, and Grebowsky, J. M.: Comparison of modeled N^+, O^+, H^+, and He^+ in the mid-latitude ionosphere with mean densities and temperatures from Atmosphere Explorer, J. Geophys. Res., 100, 257-268, 1995.

Ershova, V. A., Kochnev, V. A., Roste, O. Z. , Shultchishin, Y. A. , Šmilauer, J., and Třísková, L.: He^+ ion dominance in the high-latitude upper ionosphere as observed in "Active" experiment, Adv. Space Res., 22(6), 1381–1384, 1998.

Gonzalez, S. A., Fejer, B. G., Heelis, R. A., and Hanson, W. B.: Ion composition of the topside equatorial ionosphere during solar minimum, J. Geophys. Res., 97, 4299–4303, 1992.

Gonzalez, S. A., Sulzer, M. P. , Nicolls, M. J., and Kerr, R. B.: Solar cycle variability of nighttime topside helium ion concentrations over Arecibo, J. Geophys. Res., 109, A07302, doi:10.1029/2003JA010100, 2004.

Grebowsky, J. M., Rahman N. K., and Tylor, H. A., Jr.: Comparison of coincident 0G0-3 and 0G0-4 Hydrogen ion composition measurements, Planet. Space Sci. 18, 965-976, 1970.

Hedin, A. E.: MSIS 86 thermospheric model, J. Geophys. Res., 92, 4649–4662, 1987.

Heelis. R. A., Murphy J. A., and Hanson W. B.: A feature of behaviour of He^+ in the nightside high-latitude ionosphere during equinox, J. Geophys. Res., 86, 59–64, 1981.

Heelis, R. A., Hanson, W. B., and Bailey, G. J.: Distribution of He^+ at middle and equatorial latitudes during solar maximum, J. Geophys. Res., 95, 10 313–10 320, 1990.

Hoegy W. R., Grebowsky J. M., and Brace L. H.: Ionospheric Ion Composition from Satellite Measurements Made During 1970–1980: Altitude Profiles. Adv. Space Res., 11(10), 173–182, 1991.

Hoffman, J. H., Johnson, C. Y., Holmes, J. C., and Young, J. M.: Daytime mid-latitude ion composition measurements, J. Geophys. Res., 74, 6281–6290, 1969.

Iwamoto, I., Sagawa, E., and Watanabe, S.: Dependence of the topside ion composition on the solar flux and its implication to IRI model, Adv. Space Res., 25(1), 197–200, 2000.

Johnson, C. Y.: Ionospheric composition and density from 90 to 1200 km at solar minimum, J. Geophys. Res., 71, 1, 330–332, 1966.

Köhnlein, W.: A model of the terrestrial ionosphere in the altitude interval 50–4000 km: I. Atomic Ions (H^+, He^+, N^+,O^+). Earth, Moon, and Planets, 45, 53–100, 1989.

Lemaire J. F. and Gringauz, K. I.: The Earth's plasmasphere. Cambridge, 1998.

MacPherson, B., Gonzalez, S. A., Bailey, G. J., Moffett, R. J., and Sulzer, M. P.: The effects of meridional neutral winds on the $O^+ - H^+$ transition altitude over Arecibo, J. Geophys. Res., 103, 29 183–29 198, 1998.

Matuura, N., Kotaki, M., Miyazaki, S., Sagawa, E., and Iwamoto, I.: ISS-b experimental results on global distributions of ionospheric parameters and thunderstorm activity, Acta Astronautica, 8, 527, 1981.

Shultchishin, Y. A., Afonin, V. V., Grechnev, K. V., Ershova, V. A., Kochnev, V. A., Roste, O. Z., Smirnova, N. F., and Šmilauer, J.: Intercosmos-24: Helium ion predominance at low and mid-latitudes during equinox in the 22nd solar activity cycle, Adv. Space Res., 18(3), 15B18, 1996.

Taylor, Jr., H. A., Mayr, H. G., and Brinton, H. C.: Observations of hydrogen and helium ions during a period of rising solar activity, Space Research, vol X, 663–678, 1970.

Taylor, H. A.: Parametric description of thermospheric ion composition results, J. Geophys. Res., 78, 315–319, 1973.

Třísková, L., Truhlík, V., Šmilauer, J., and Shultchishin, Yu. A.: Comparison of O^+/H^+ and $O^+/(H^+ + He^+)$ Transition Levels, Adv. Space Res., 22(6), 897, 1998.

Třísková, L., Truhlík, V.,and Šmilauer, J.: On possible improvements of outer in composition model in IRI. Adv. Space Res., 29(6), 849–858, 2002.

Třísková, L., Truhlík, V., and Šmilauer, J.: An empirical model of ion composition in the outer ionosphere. Adv. Space Res., 31(3), 653–663, 2003.

Truhlík, V., Třísková, L., and Šmilauer, J.: Improved electron temperature model and comparison with satellite data. Adv. Space Res., 27(1), 101–109, 2001.

Truhlík, V., Třísková, L., and Šmilauer, J.: Empirical Modeling of the Upper Transition Height for Low and Middle Latitudes, Adv. Space Res., 27(1), 111–114, 2001.

Truhlík, V., Třísková, L., Šmilauer, J., and Iwamoto, I.: Comparison of a new global empirical ion composition model with available satellite data, Adv. Space Res., 31(3), 665–675, 2003.

Truhlík, V., Třísková, L., and Šmilauer, J.: New advances in empirical modelling of ion composition in the outer ionosphere. Adv. Space Res., 33(6), 844–849, 2004.

West K. H., Heelis R. A., and Rich F. J.: Solar activity variations of the low-latitude topside ionosphere, J. Geophys. Res., 102, 295–305, 1997.